Possible Photometric Evidence of Ejection of Bullet Like Features in the Relativistic Jet source SS433

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ABSTRACT

SS433 is well-known for its precessing twin jets having optical bullets inferred through *spectroscopic* observation of H_α lines. Recently, Chakrabarti et al. (2002) described processes which may be operating in accretion disk of SS433 to produce these bullets. In a recent multi-wavelength campaign, we find sharp rise in intensity in time-scales of few minutes in X-rays, IR and radio waves through *photometric* studies. We interpret them to be possible evidence of ejection of bullet-like features from accretion disks.

Subject headings: SS433 — X-ray, Infra-red and radio sources — stars: individual (SS 433) — stars: winds, outflows, mass loss

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1. Introduction

SS433 is a well studied bright emission line compact system which is ejecting matter in symmetrically opposite directions at a speed of $v_{jet} \sim 0.26$c. It has a mass-losing ($\dot{M} \sim 10^{-4} M_\odot$/yr) companion orbiting in 13.1d. The jets are precessing in 162.15d around the symmetry axis. The velocity is remarkably constant to within a percent or so (Margon, 1984; Gies et al. 2002). As a result of the remarkable constancy in the precession time scales and the velocity, the instantaneous locations of the red and blue-shifted H_α lines are well predicted by the so-called 'kinematic-model' (Abell & Margon, 1979) and the compilation

of twenty years of timing properties (Eikenberry et al. 2001) suggest that kinematic model can explain the general variation of the red and blue-shifts very well.

A very exciting observation, made within years of the discovery of SS433, suggests that the passage of the jets is not continuous, but as if through successive and discrete bullet-like entities, at least in the optical region (Grandi, 1981; Brown et al. 1991). The H_α lines were seen to brighten up and fade away without changing their red/blue-shifts, indicating the brightened bullets are radially ejected and do not have any rotational velocity component. Since the bullets of energy $\sim 10^{35}$ ergs do not change their speed for a considerable time ($\sim 1-2$ days), Chakrabarti et al (2002) postulated that they must be ejected from accretion disk itself. They presented a mechanism to produce quasi-regular bullets. Using results of numerical simulations involving oscillation of shocks in accretion disks, they concluded that in the normal circumstances, $50 - 1000$s interval is expected in between the bullet ejection. These bullets would be ejected from X-ray emitting region and propagate through optical, infra-red ($\sim 10^{13-14}$cm) and finally to radio emitting region at $\gtrsim 10^{15}$cm (roughly the distance covered in a day with $v \sim v_{jet}$) or so. Thus if the object is in a low or quiescence state, each individual bullet flaring and dying away in a few minutes time scale, should be observable not only in optical wavelengths (Grandi, 1981; Margon, 1984; Brown et al. 1991; Gies et al. 2002) but also in all the wavelengths, including X-ray, IR and radio emitting regions. So far, no such observations of individual bullets has been reported in the literature and it was necessary to make a multi-wavelength observation at relatively quieter states.

In this *Letter*, we present some results of our multi-wavelength studies. From the long term analysis of radio flares (Bonsignori-Facondi, Padrielli, Montebugnoli and Barbieri, 1986; Vermeulen et al. 1993) it is known that in between big flares which occupy $\sim 20\%$ of the time the object may go to very quiescence state. So, it is likely that one could 'catch' these bullets in action provided observations are carried with very short time resolution. Our multi-wavelength observations lasted during 25th of Sept., 2002 to 6th of October, 2002 with X-ray, infra-red, optical, radio observations made simultaneously on the 27th of September, 2002. Here, we report only X-ray, infra-red and radio observations of 27th and 29th of September, 2002. Optical studies required longer integration times and these results along with other days of observations would be reported elsewhere (Chakrabarti et al. 2003).

Our main results indicate that there are considerable variations in the timescale of minutes in all the wavelengths. These may be called micro-flares. When Fourier transform is made, some excess power is observed in $2 - 8$ minutes time scale (often beyond 3σ level). The X-ray count rate was found to increase by $15 - 20\%$ within a minute. Since the emitting regions of X-ray, IR and radio are not well known with absolute certainly, while duration of the flares last less than a few minutes, we could not prove beyond doubt that there are indeed

correlations among the micro-flares observed in these wavelengths. However variabilities we find are not flicker type or shot noise type in the sense that the power density spectrum (PDS) is not of $1/f$ type and the duration is not very short (i.e., < 1s). We therefore believe that we may have found evidences of bullet ejection through these observations in other wavelengths.

2. Observations and Data Reduction

Radio observation was carried out with Giant Meter Radio Telescope (GMRT) at 1280MHz (bandwidth 16 MHz) which has 30 antennas each of 45m in diameter spreaded over 25km region (Swarup et al. 1991) near Pune, India along roughly Y shaped array. The data is binned at every 16 seconds. On 27th and 29th of September, 2002, no. of antennas working were 28 and 13 respectively. AIPS package was used to reduce the data. Bad data was flagged using tasks UVFLG and TVFLG and the standard deviation at each time bin using UVPLT package was computed. On 27th, 3C48 and 3C286 were used as the flux calibrator while on the 29th only 3C48 was used. Generally, the observation condition was very stable.

Infrared observation was made using Physical Research Laboratory (PRL) 1.2m Mt. Abu infrared telescope equipped with Near-Infrared Camera and Spectrograph (NICMOS) having 256 $\times$ 256 HgCdTe detector array cooled to 77K. The filters used were standard J (λ=1.25 μm, $\Delta\lambda$= 0.30 μm), H (λ=1.65 μm, $\Delta\lambda$= 0.29 μm) and K$'$ (λ=2.12 μm, $\Delta\lambda$= 0.36 μm) bands. The observational data on 27th of September, 2002 for J and H bands are binned at every 10 seconds while that of K$'$ band is binned at every 20 seconds. The data reduction was performed using the IRAF software package. All the object frames were de-biased, sky-subtracted and flat-fielded using normalized dome flats. The sky frame was created by usual practice of median combining of five position dithered images in which the source was within the NICMOS field of $2' \times 2'$. At each dithered position ten frames were taken with each integration time of 10 seconds. The nearby infrared bright standard star GL748 (Elias et al. 1982) was used as the calibrator and it was observed for at least 15 minutes at each filter band. We measured the stellar magnitudes using the aperture photometry task (APPHOT) in IRAF. Our derived mean JHK$'$ magnitudes on Sept. 27th are 9.47$\pm$0.02, 8.48$\pm$0.02 and 8.32$\pm$0.02 respectively and the corresponding mean flux densities are 0.261$\pm$0.002, 0.413$\pm$0.003 and 0.305$\pm$0.003 respectively. The magnitudes are converted to flux density (Jansky) using the zero-magnitude flux scale of Bessell, Castelli & Plez (1998). To estimate reddening, we assumed visual extinction A_v =8.0 (Gies et al. 2002). Using the relation given in Bessell, Castelli & Plez (1998) the JHK$'$ extinctions were found to be A_J=

2.32, $A_H = 1.84$, $A_K = 0.88$. The de-reddened flux in JHK$'$ are 2.24 Jy, 2.21 Jy and 1.67 Jy respectively. The differential magnitudes are determined using two brightest stars (std1: J= 12.1, H=10.6, std2: J=12.5, H= 11.1 mag) in the same frame of the object. The error in individual flux density measurement is usual propagation error of the observed photometric magnitude. Photometric errors ϵ are calculated for individual frame of every star and for the subtracted differential magnitude the final error was calculated as $\sqrt{\epsilon_1^2 + \epsilon_2^2}$, where ϵ_1 and ϵ_2 are the error-bars of the individual stars.

X-ray observation was carried out using Proportional Counter Array (PCA) aboard RXTE satellite. The data reduction and analysis was performed using software (LHEASOFT) FTOOLS 5.1 and XSPEC 11.1. We extract light curves from the XTE/PCA Science Data of GoodXenon mode. We combine the two event analyzers (EAs) of 2s readout time to reduce the Good Xenon data using the perl script **make_se**. Once **make_se** script was run on the Good_Xenon_1 and Good_Xenon_2 pairs, the resulting file was reduced as Event files using **seextrct** script to extract light curves. Good time intervals were selected to exclude the occultations by the earth and South Atlantic Anomaly (SAA) passage and also to ensure the stable pointing. We also extracted energy spectra from PCA **Standard2** data in the energy range 2.5 - 20.0 keV (out of five PCUs only data from 0, 2, 3 PCUs are added together). For each spectrum, we subtracted the background data that are generated using PCABACKEST v4.0. PCA detector response matrices are created using PCARSP v7.10.

3. Results on short time-scale variabilities

The observational result of September 27th, 2002 is shown in Fig. 1 with UT (Day) along the X-axis. The upper and middle panels show the radio and IR fluxes (uncorrected for reddening) in Jansky and the lower panel shows X-ray counts per second in $2-20$keV. Typical error-bars of the mean-flux measurements (standard deviation in each time bin for radio and IR, and squared-root of counts per binsize for X-rays) which are included in the Figure are: in radio $\sim$ 1mJy, in IR 0.5mJy and in X-ray $\sim$ 3 counts/s. These observations correspond to an average flux of 10^{-14}ergs/cm^2/s, 5×10^{-10}ergs/cm^2/s and 10^{-10}ergs/cm^2/s respectively. In other words, assuming isotropic emission, at a distance of 3kpc for the source, the average radio, IR, and X-ray luminosities are 1.1×10^{30} ergs/s, 5.5×10^{34}ergs/s and 10^{35}ergs/s respectively. Observations in radio and IR were carried out during 25-30th September, 2002 and no signature of any persistent ‘flare’ was observed. The radio data clearly showed a tendency to go down from 1.0Jy to 0.7Jy reaching at about 0.3Jy on 28th/29th, while the X-ray data showed a tendency to rise towards the end of the observation of the 27th. The IR data in each band remained virtually constant. The H-band result was found to be higher

compared to the J and K′ band results during 25th-29th September, 2002. A similar result of turn around at about 4 micron was reported earlier by Fuchs (2003). This turn over could be possibly due to free-free emission in optically thin limit. Detailed discussion will be presented elsewhere (Chakrabarti et al. 2003).

In Fig. 2, we present the same light curves as in Fig. 1 but plotted around the 'local' mean, i.e., mean values taken in each 'spell' of observation. We note that there are significant variations in a matter of minutes in observations at all the wavelengths. From eye-estimate, we see variability time-scale to be $T_{var} \sim 2 - 8$ minutes. The error-bars include errors in individual measurements plus the standard deviation of the flux variation in the light curve. To impress that the variability is real, we show in Fig. 3 the differential flux density variation of IR observations in the J and H bands during 27 September 2002 using differential photometry. The error-bars are also shown. The 1 σ error-bar (J=0.00035 Jy, H= 0.00085 Jy) of the differential flux variation between SS433 and std1 for the whole light curve is a factor of 3.5 and 2.5 in the J-band and H-band respectively in comparison to that between two standards (J=0.0001 Jy, H=0.00035 Jy). The 1 σ for the light curve is more than a factor of 5σ of single point measurement error. Thus, the variation in the IR light curves of SS433 is likely to be intrinsic and the analysis shows above 2σ level variability in both bands.

Could these variations be due to individual bullets? In order to be specific, we present in Fig. 4a, one 'micro-flare'-like event in radio from the data on 29th of Sept., 2002, when radio intensity was further down ~ 0.3Jy so that the micro-flares could be prominently seen. Here 0s corresponds to 15h35m UT. We observe brightening the source from 0.35Jy to 0.8Jy in $\sim$ 75s which faded away in another $\sim$ 75s. That is, the intensity became more than doubled in $\sim$ 1 minute! Similarly in Fig. 4b, where we presented a 'micro-flare' from the 2nd (central) 'spell' of X-ray data of 27th Sept. 2002 (Fig. 1-2), we also observe significant brightening and fading in $\sim$ 100s. Here 0s corresponds to 16h5m UT. The count rate went up more than 15% or so in about a minute. The energy contained in the radio micro-flare, integrated over their lifetime is about $I \nu \tau 4 \pi D^2 10^{-23} = 1.1 \times 10^{33}$ergs (Here, $I \sim 0.8$ is the intensity in Jansky, $\nu = 1.28 \times 10^9$Hz is the frequency of observation, $\tau \sim 100s$ is the rise-time of the bullet, $D = 9 \times 10^{21} cm$ is the distance of SS433). Similarly, the energy contained in the X-ray micro-flare is about $\frac{1}{2}\tau(N_{\gamma,max} - \bar{N}_\gamma)E_\gamma 4\pi D^2/A_{PCA} = 2.7 \times 10^{35}$ergs (Here, $\tau \sim 100s$ is the rise-time of the flare, $N_{\gamma,max}$ is the maximum photon count rate, $\bar{N}_\gamma$ is the average photon number, E_γ is the average photon energy, A_{PCA} is the area of the PCA detectors.). The spectroscopic study yields an average flux of 2.41×10^{-10} ergs/cm^2/s. With an estimated duration of 100s, and about 15% energy going to the micro-flare (Fig. 4b), one obtains the micro-flare energy to be 4.1×10^{35} ergs in general agreement with the result obtained from photometric study. Since the radio luminosity is very small, even when

integrated over 0.1 to 10GHz radio band (with a spectral index of ~ -0.5) (Vermeulen et al, 1993) we find that almost all the injected energy at X-ray band is lost on the way during its passage of $\sim 1-2$d.

Though the variations we find are not periodic (strictly speaking they are nor expected to be periodic, either), the power-density spectrum (PDS) does show considerable power in frequencies $\sim 0.002 - 0.008$Hz. Deviation of the PDS from a power-law background $\propto \nu^{-\alpha}$ (e.g., Mineshige, Ouchi & Nishimori, 1994) in all three bands gives an estimate of excess power at low-frequencies. We fit $\alpha = 1.8$ for X-ray power, 1.9 for IR power, and 1.6 for radio power in PDS. X-ray power shows excess at ~ 0.003Hz ($> 2.7\sigma$), i.e., at $T_{var,x} \sim 5.5$ min. and at 0.0077Hz ($> 1.4\sigma$), i.e., at $T_{var,x} \sim 2.1$ min. IR power shows excess at 0.0022Hz ($> 4\sigma$), i.e., $T_{var,ir} \sim 7.7$ min. Radio PDS shows excess at ~ 0.0023Hz ($> 3.2\sigma$) i.e., at $T_{var,r} \sim 7.2$ min. and at ~ 0.003Hz ($> 1.6\sigma$), i.e. at $T_{var,r} \sim 5.5$ min. respectively. Here 1σ error in residual power is the standard deviation computed separately for each PDS after subtracting the power-law background $\nu^{-\alpha}$. Because the peaks in PDS are often marginally significant we do not claim that we see quasi-periodic oscillations that are observed in numerous black hole and neutron star candidates.

In order to establish that the features we observe are really due to 'bullets' emitting at different wave bands, one should find correlations among them, or try to 'follow' them from one band to the other. Unfortunately, cross-correlation among our observations did not yield sharp peaks, partly because the observations were of short duration. Main problem is that the locations of the IR/radio emitting regions themselves are very uncertain. Also, the average duration of an 'event' ($\sim$ minute) and average interval of the events ($2-8$ minutes) are very very short compared to the travel time of the bullets to IR ($\sim 10^4$s) or radio ($\sim 10^5$s) regions. However, we can exclude that the variabilities to be due to 'fluctuations' at the inner regions of the accretion disk – the typical time-scale of such variabilities (say, at $r \sim 3r_g$, where, $r_g = 2GM/c^2$, M, G and c being the mass of the black hole, G being the gravitational constant and c being the velocity of light) of an $M = 10M_\odot$ object would be $\sim 2\pi r/c \sim 20GM/c^3 \sim 10^{-3}$s, i.e., of much shorter duration than what we see. Similarly, has it been due to random or flicker noise, we should have seen $1/f^\alpha$ ($\alpha \sim 1$) dependence of the PDS. However, the best fit of PDS has $\alpha \sim 1.6 - 1.8$ instead. Thus, the origin of these features must be different and could be due to bullet-like ejections from the disk.

In the spectrum, we find two strong Fe line features in all the three spells of X-ray observation. The best fit was found to be the thermal bremsstrahlung model with two Fe lines ($kT \sim 18$keV) having a reduced χ^2 of around 1.2 in each case. We failed to fit with a model having a blackbody emission component. Thus, no evidence for a Keplerian disk was found. The average flux was found to be 2.3×10^{-10} ergs/cm^2/s. This corresponds to a

luminosity of 2.5×10^{36} ergs/s. Since a bullet has about $10-15\%$ of the total count (Fig. 4b), each bullet will have an energy of around 2.5×10^{35} ergs/s.

4. Concluding remarks

In this *Letter*, we presented results of our multi-wavelength observations which were save at short time intervals. From the analysis of the observations of radio, IR and X-ray in the quiescence state we conclude that we may be observing ejection events of bullet-like features from the accretion disk in time scales of $\sim 2-8$ minutes. Identification of small micro-flare events with those those of bullet ejection is derived from the time scales of variabilities, which are roughly the same in all these wavelengths. We find their presence in X-ray ($\lesssim 10^{11-12}$cm), IR ($\lesssim 10^{13-14}$cm) and radio ($\lesssim 10^{15}$cm) emission regions. Vermeulen et al. (1993) found evidence for optical bullets with life-time of $1-2$d. This is perhaps due to the propagation of a burst of indistinguishable bullets and not due to a single one. We identified micro-flare like features in all these observations which may be signatures of the bullets. Count rate of X-ray was seen to increase $15-20\%$ in a matter of a minute. One way to actually identify each bullet could have been to follow them from X-ray region outwards. This will require very careful time delay measurements since the distances of emission regions are not very accurately known to follow a feature of duration of a minute. We exclude the possibility that what we see were flicker noise since neither the duration nor the PDS properties match with those of flicker noise. One could have perhaps distinguished the energetic bullets by observing polarization properties of the radio-emissions during the short-lived flares, but unfortunately due to technical reason this observation could not be carried out. We plan to do such an observation in near future.

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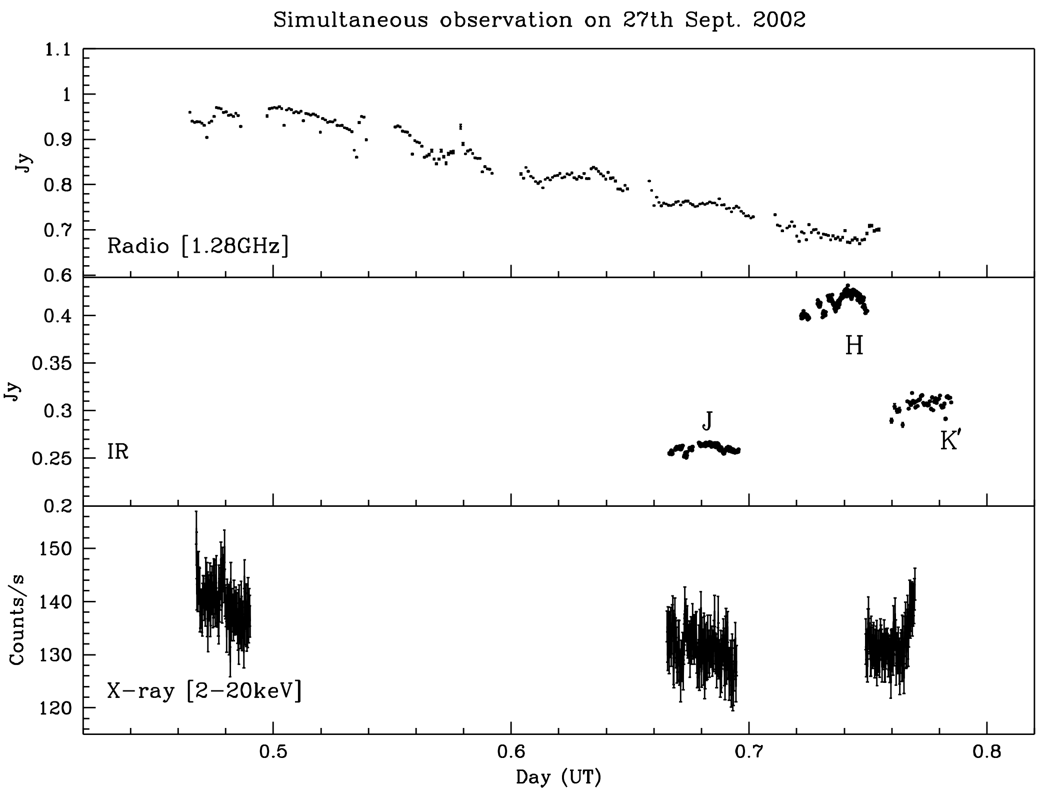
Fig. 1: Multi wavelength observation of short-time variability in SS433 by Radio (upper panel), Infra-red (middle panel) and X-ray (lower panel) on 27th of September, 2002. The observations were made at Giant Meter Radio Telescope, Pune at 1.28GHz (Radio), 1.2m Mt. Abu Infra-red Telescope at J, H and K' bands and RXTE satellite (2-20keV) respectively.

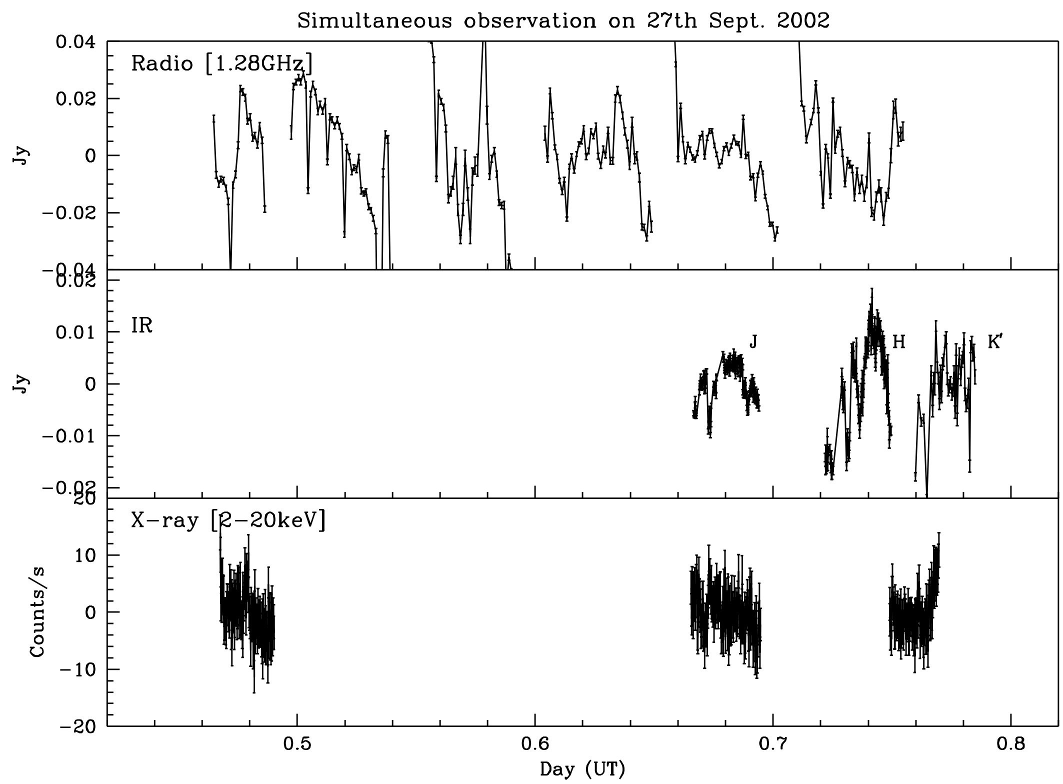
Fig. 2: Observations at in Fig. 1 are plotted around mean taken in each spell of observation. Considerable variations at time scale of a few minutes are observed.

Fig. 3: Differential photometry of SS433 with respect to two brightest standard stars (std1 and std2) in the same frame of the object are plotted. Different curves are marked on upper-right corner in each panel. X-axis of the graph is the relative time of measurements in seconds. The error bar for each individual differential measurements are also shown. Differential flux variation of SS433 is above 2σ level in comparison that of standards.

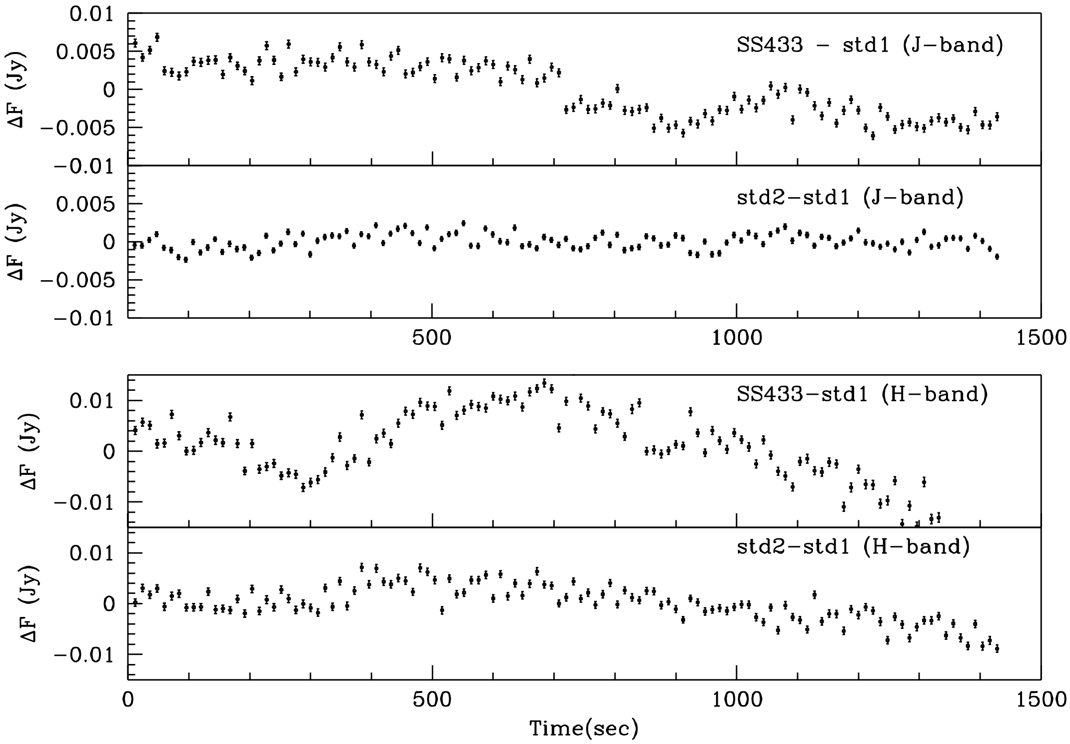
Fig. 4: Individual flares in very short timescales are caught. (a) A radio flare lasting 2.5 minutes (observed on 29th Sept. 2002) and (b) an X-ray flare (observed on 27th of Sept. 2002) lasting for about 3.5 minutes. Each bin-size is 16s.



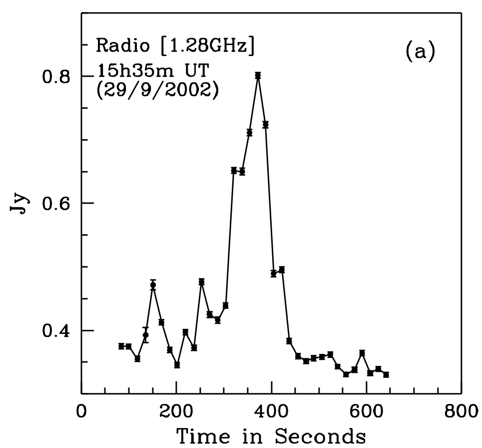
Simultaneous observation on 27th Sept. 2002
Jy
Radio [1.28GHz]
1.1
1
0.9
0.8
0.7
0.6
Jy
IR
H
J
K′
0.4
0.35
0.3
0.25
0.2
Counts/s
X-ray [2–20keV]
150
140
130
120
0.5
0.6
0.7
0.8
Day (UT)

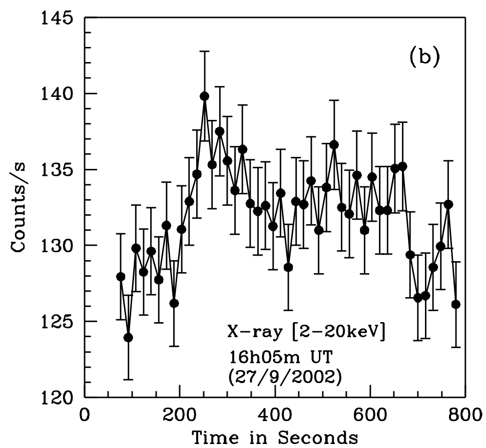


Simultaneous observation on 27th Sept. 2002
Radio [1.28GHz]
Jy
0.04
0.02
0
−0.02
−0.04
IR
J
H
K'
0.02
0.01
0
−0.01
−0.02
X−ray [2−20keV]
Counts/s
20
10
0
−10
−20
0.5
0.6
0.7
0.8
Day (UT)



SS433 – std1 (J–band)
std2–std1 (J–band)
SS433–std1 (H–band)
std2–std1 (H–band)
ΔF (Jy)
Time(sec)
0.01
0.005
0
−0.005
−0.01
500
1000
1500
0


Radio [1.28GHz]
15h35m UT
(29/9/2002)
(a)
Jy
0.8
0.6
0.4
0
200
400
600
800
Time in Seconds



(b)
X-ray [2-20keV]
16h05m UT
(27/9/2002)
Counts/s
Time in Seconds
145
140
135
130
125
120
0
200
400
600
800